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Volume 3

Ground Network Architecture

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Technical Feasibility of Digital Three-Dimensional Cellular Communications for Air Traffic Control Applications

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ABSTRACT

MITRE's Center for Advanced Aviation System Development (CAASD) has proposed a set of concepts for improving VHF communications for air traffic control applications. One idea, called CTAG for Cellular Trunked Air Ground (CTAG) communications is to extend land-mobile cellular-trunked digital communications technology to air-ground communication between pilots and controllers. This study was aimed at addressing the technical feasibility of this approach. Detailed results show that significant benefits can indeed be obtained in not only automating routine communications functions but also in reducing the number of frequency channels required compared with existing analog voice-only procedures. Further work is required to quantify potential system costs, particularly those associated with the ground portions of the CTAG network.

PREFACE

This report is subdivided into three volumes. Volume 1 is the Introduction and Summary which contains an overview of the entire report including background, requirements, assumptions, and a summary of the principal results. Volume 2 contains Example System Design Details on all but the Ground Network Architecture work. The latter is contained in Volume 3.

VOLUME 3 ACKNOWLEDGMENTS

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SECTION 11

INTRODUCTION

The Cellular Trunked Air Ground (CTAG) Radio communications concept has as its technical origin the MITRE Paper MP-90W00017, dated January 1991, entitled, "Cellular-Trunked Air/Ground Radio (CTAG): A Concept for Improving Aeronautical Communications," by Ronald L. Richards, Thomas R. Lehnert, and Lisandro del Cid.

CTAG is a proposed concept that is envisaged to alleviate a number of problems facing the present air/ground VHF radio system used for air traffic control in the United States including (1) increases in demand for channel capacity; (2) the desirability of automatic routine frequency changes to alleviate pilot and controller workload; and (3) the needs to provide digital services and interfaces. In a departure from the present analog VHF air/ground (A/G) radio system, CTAG proposes to make use of the technical practices and principles of present-day cellular mobile radiotelephony systems, as well as those of current automated trunked bi-directional land radio systems. Explicit in the CTAG concept is the use of proven technology which may be developed at low risk and reasonable cost. Implicit in it as well is the increased use of modern digital communications and processing.

The present scope of CTAG encompasses air/ground voice communications between pilots and ground controllers. However, it is expected to have important interfaces with the data link information to be conveyed across the future Aeronautical Telecommunication Network (ATN), and would also be a component of the overall National Airspace System (NAS) architecture.

The purpose of this report is to present a proposed first-level definition of the ground transmission and switching system that would support the CTAG communications concept. The scope of this document is confined to the portion of the CTAG system that provides ground communications, up to interfaces with the CTAG VHF ground and airborne radio systems. Additionally, the scope of the ground system definition activity includes identification of technologies, techniques, and connectivities which would support an initial CTAG network design, performance of initial network sizing, solving of concept problems, identification of pertinent standards, protocols, and interfaces, and exploration of operational issues which might pertain to design and extension of CTAG.

Cost estimation of the CTAG ground network, although vitally important to furthering the CTAG concept, was not possible in this initial phase. This task must await continued funding but is the highest priority next step in the CTAG investigation.

CTAG must meet or exceed the following parameters, which are requirements set by the Federal Aviation Administration (FAA) operations for A/G VHF radios [Reference 1]:

a. Voice transmission initiation time for air-ground service is 250 ms.
b. Continuous pilot access to NAS facilities is required.
c. A service availability of 0.99999 must be achieved.

These parameters, and the fact that VHF A/G communications are considered "critical" by the FAA, demand a high degree of reliability and robustness of the ground system that supports CTAG.

SECTION 12

CURRENT MOBILE RADIO TELEPHONE

The ground system definition tasking for CTAG is a basic component of the CTAG MITRE-Sponsored Research (MSR) effort. The basic infrastructure of a radio-based cellular communications system or a system of trunked radios depends upon a circuit-switched telecommunications system. As both of these systems are an outgrowth of the public switched telephone network (PSTN), evolution of these systems has occurred in a more or less incremental way. CTAG will be different. At the present time, the circuit-switched communications systems used by the National Airspace System (NAS) is dedicated to voice telephony purposes, and is largely disjoint from the present A/G VHF AM radio system. For CTAG, a ground-based telecommunications structure will have to be developed.

Cellular mobile telephony operation has been established to obviate the clear operational limitations of present-day conventional-type mobile telephone: inadequate performance, limited capability, and inefficiencies of spectrum use. In the past, service performance was restricted, since only thirty-three channels were available for three different mobile telephone systems. Waiting lists for customer service were long (several thousand, and blocking probabilities were high during busy hours. As for service capability, a user of ordinary mobile telephone service must reinitiate a call whenever the mobile unit passes out of service range of the single zone of (antenna) coverage. This is an inefficient system, since without handoffs, it is uncertain whether an arbitrary call may be completed without premature dropout. Inefficiencies of spectrum use need no explanation: a conventional mobile system can only serve a single customer at a time in an entire area or zone. Frequency reuse in cellular systems provides a much more efficient use of a limited and "valuable" resource, available radio frequency spectrum.

In general, a cellular telephone system consists of four major components: (1) the mobile units, (2) the cell sites or base stations, (3) the mobile telephone switching office (MTSO) or master switch, and (4) the connectivity among the first three components. This paragraph summarizes each of these components. First, each mobile unit consists of a control unit, radio transmitter and receiver, and an antenna system. Second, the cell site or base station is the component that provides an interface between the mobile units and the MTSO. Cell sites contain control units, data terminal equipment, base station radio equipment (transmitters and receivers), ground antenna systems, and their own power systems. Third, the MTSO is the master switching office and coordinating component for all the cell sites served by it. The MTSO contains the cellular processor and cellular circuit switch, and provides the interfaces with PSTN zonal offices. It also controls all call processing and accounting activities. Finally, the connectivity among the mobile units, the cell sites, and the MTSO is provided by radio and high-speed data links. Although each mobile unit may only use one channel at a time for a communications link, this channel is not a fixed one. It may assume any one of the channels assigned by a serving area. Also, each site has multichannel capabilities that provide simultaneous connections to many mobile units.

A cellular telephone system has five major procedures in its operation. First, a mobile unit is initialized upon power-up. Second, a mobile unit may originate a call; third, a fixed or ground network unit may originate a call. Fourth, the mobile unit terminates a call. And fifth, handoffs occur from time to time. Short summaries of these procedures follow.

A mobile (or automobile-based) user powers up the unit receiver, and it scans a number of service channels and selects one with the strongest signal-to-interference ratio, and locks onto it. This usually is the nearest cell site. This scheme is called self-location, and is repeated at intervals of usually one minute. Future systems will use a digital registration of a mobile terminal upon powerup.

To originate a call, a mobile end user enters the called number into a register in the mobile unit, checks it visually, and sends it outward. This results in a request for service sent on a selected service channel. The cell site equipment receives it and also sends the request to the MTSO, or master switch, on a high-speed data link. The switch selects a voice channel for the call and uses the cell site equipment to establish the radio link between end equipment. The switch also makes the connection between the called party through the PSTN local office.

To originate a call from a fixed telephone, that party dials the number of the mobile unit. The local PSTN central office can derive from its database that the called party is a mobile unit and forwards the call connect request to the MTSO, which thereupon sends a paging message to candidate cell sites based upon the mobile unit's number and a search algorithm. The cell sites transmit the page request on the service channels. The called mobile unit responds to its own page on a service channel with a high signal-to-interference ratio, locks onto that service channel, responds to the cell site request, tunes to the requested voice channel frequency, and alerts the end-user of an incoming call.

Call termination is simple. The mobile user powers down the transmitter, the signaling tone is transmitted to the cell site equipment, and the cell site and mobile unit clear the connection. The mobile unit then continues to monitor paging through the service channels.

Handoffs occur as follows. After a call is established to a mobile telephone subscriber, the radio channel must be monitored for quality, and when the quality deteriorates below a predetermined threshold, the call must be transferred to a cell which can provide improved reception/transmission. When monitoring the channel, the central controller knows nothing about the mobile unit (location, speed, direction of travel) except received signal level on the voice channel in use, and the cell providing the channel. When the signal level drops below a predetermined threshold, the central controller then monitors that frequency at each of the adjacent cells and begins the procedure to assign the mobile a channel in the cell with the best received signal.

The cellular radiotelephone service architecture bears as an implicit assumption that the ground-based wireline PSTN exists. Thus, cellular radio architectures to date have been overlays onto a ground network, with MTSOs connecting with other MTSOs and to non-cellular switches through the public network hierarchy.

At the present time, cellular telephone systems are being deployed worldwide. Although the present operational generation of cellular telephone is analog, and based upon the fundamental work done on the Analog Mobile Phone System (AMPS), incompatibilities among the various systems exist. There are also plans for conversion to digital cellular systems, many of which are interoperable with integrated service digital networks (ISDNs). This generation is still in the planning stages, with a number of digital modulation schemes proposed, using not only frequency-division multiple access (FDMA) and time-division multiple access (TDMA), but also spread-spectrum, i. e., code-division multiple access (CDMA) techniques. For the ground infrastructure, most systems envisage use of Signaling System #7 for interswitch signaling and control.

Present problems experienced include interoperability problems when a mobile subscriber transits a common carrier boundary. These roamers must be registered in some manner by the databases of the MTSO of the carrier area into which they have entered, and accounting problems may ensue. A more pressing problem is loss of signal due to handoffs to non-optimal cell sites. This is mainly due to the criteria applied to each mobile unit for location of the optimal new cell site for handoff, and may be subject to improvement, if better mobile unit location information were available.

The commercial cellular radiotelephone environment has a number of common and specialized carriers providing service, and manufacturers of both radio and circuit switching equipment providing equipment, not only in the United States, but worldwide. Deployment of mobile units in the United States is now in the several millions; coverage of populace in some regions, such as Scandinavia, is even higher (up to 40%). The applicability to CTAG is clear; much of the equipment and techniques used in the design, development, and provisioning of modern cellular and trunked radio systems may be transferrable to the CTAG environment. The air traffic control function, however, does impose its unique operational constraints, such as stringent end-to-end response requirements. In addition, the relatively high percentage of handoffs to suboptimal cell sites in the commercial sector (up to 10-25% in some cases) would not be tolerated in the FAA environment.

SECTION 13

CTAG GROUND SYSTEM ARCHITECTURE

In general, there are three types of system architectures currently used for digital cellular switching:

- Centralized
- Decentralized
- Remote Control

Centralized systems for digital cellular switching resemble those of analog systems. Examples of large, centralized, digital cellular telephony switching systems available today are:

- Motorola EMX2500
- Ericsson AXE-10
- Northern Telecom DMS-MTXM

Generally, centralized systems have only a single level of control, and the use of call processing is relatively low, compared to a decentralized system. Additionally, the call set-up time for a central control system is less than that for a decentralized system. Centralized systems deal with heavy traffic loads, making them useful for a high-traffic environment. However, there is a single point of failure, the central switch.

Decentralized systems treat all switches in the system as peers. This means that there is no central, or main decision-making switch and therefore, no single point of failure. An example of a decentralized, digital cellular switching system is the AT&T Autoplex 1000. Such a system contains an executive cellular processor, an interprocess message switch, the digital switches themselves, an interswitch peripheral control, and interconnection modules. In general, a decentralized system has more than one control level. This makes the use of call processing higher than that of a centralized system. Also, the increased levels of call control cause greater call processing use and longer call set-up times for each call. In principle, decentralized systems allow growth by the addition of a module, and have more flexibility in coping with capacity increase requirements. The increased call processing and call set-up delay must be traded off against the lack of a single point of failure. In general, a decentralized system should be able to deal with a disabled switch by routing and switching calls to other nodes.

In a remote control system architecture, a main switch is used to control remote secondary switches. This means that there is a hierarchy of switches in the network. This is contrasted against the decentralized approach, in which each switch is an equal and against the centralized approach where all subscriber lines and trunks are connected to one large switch. Current research has not revealed any implementation of the remote control system architecture.

Each architecture has advantages and disadvantages in the CTAG environment. At the present time, the amount of call processing and call set-up delays incurred by a system of decentralized digital cellular switches has not been determined. However, the amount of these delays are not expected to be significant, as call set-up is expected to occur long before the actual switching function is required. Also, the practical advantage of a network of peer switches is high, since it appears to be impractical to operate a single central switch for all CTAG call processing. The two major problems of using a single central master switch for CTAG are those of call processing and connectivity. First, a centralized architecture would place the burden of nationwide call processing onto a single switch, and that switch would require many times the reliability of each switch in a network (single point of failure). Second, a centralized star topologically would require a transmission network many times the size of that of a system of backbone switches. Therefore, the CTAG switching architecture described in the following paragraphs is based on a system of decentralized digital cellular switches.

13.1 CTAG GROUND MASTER SWITCH (CGMS) NETWORK

Based on the selection of a decentralized system architecture, the CGMS network will consist of interconnected peer switches. The following subsections provide details on network topology, switch hierarchy, and switch location .

13.1.1 Network Topology

The proposed CTAG network topology consists of a mesh type architecture. The primary consideration is that of the location, type, and traffic requirements for the primary switches, also known as the CTAG Ground Master Switches, or CGMSs. For network survivability purposes, each CGMS should be connected to at least two other CGMS locations, one path being the primary connectivity and the other path being the alternate connectivity. Figure 13-1 provides a possible set of CTAG CGMS locations and interconnectivity. It is assumed that the CGMS is collocated with the ARTCC.

The CGMS backbone connection in the figure states the information bandwidth required in numbers of T-1 connections, each at an aggregate transmission rate of 1.544 Mb/s, and consisting of twenty-four 64-kb/s PCM channels and framing and synchronization overhead. This bandwidth analysis lists the maximum requirement, as a first-order estimate. More precise analysis and refinement will reduce the transmission requirement. For example, use in the backbone of 32-kb/s adaptive differential pulse code modulation (ADPCM) vice PCM could halve the number of T-1 trunks required (NOTE: CCITT Recommendation G.721 provides direct digital 32-kb/s ADPCM to 64-kb/s PCM transcoding in transmission systems without loss of resolution or bit sequence integrity for typical 3.1-kHz voice).

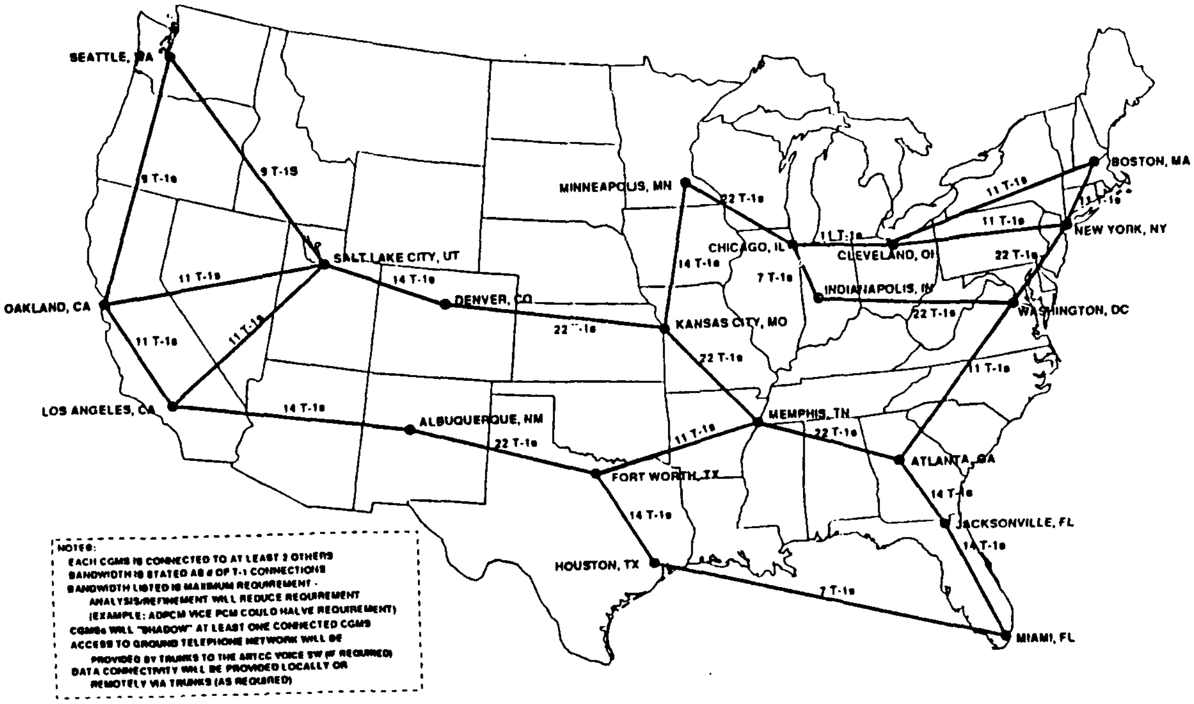


Figure 13-1. CTAG CGMS Locations and Interconnectivity (Colocated w/ARTCC)

The CGMSs will "shadow," and maintain a connectivity database for, at least one connected CGMS, such that connectivity to cell sites and users if any CGMS is down may be provided by alternate routes through the back-up CGMSs. Access to the network for ARTCC, TRACON, and tower controllers is expected to be provided by trunks to the ARTCC Voice Switching and Control System (VSCS). Trunks to the VSCS will also provide access into the ground telephone network, if required. Additionally, data connectivity will be provided locally or remotely via access lines to computer equipment, as required.

The CGMS interconnectivity is derived from the following set of rules that provide for rough calculations for the number of T-1 connections between the CGMSs. Note that the connectivity between the 20 CGMS areas is used to provide directly-connected CGMS end-users with back-up connectivity in instances in which the primary CGMS fails. However, specific CGMS-to-CGMS connections were selected arbitrarily, and further analysis must be accomplished in order to determine the optimum network.

<u>Rules:</u>

1. The primary back-up route must provide sufficient capacity for all end-users to connect to the backup switch (CGMS) simultaneously.

2. The alternate back-up route does not necessarily have to provide capacity for all users to have simultaneous connectivity. (Capacity for at least half the users to be connected simultaneously is provided).

3. Each user's voice channel will utilize CCITT Recommendation G.711 PCM encoding (μ-law as for North America) and will require an end-to-end 64-kb/s channel.

4. It is allowable to traverse <u>one</u> intermediate station for up to half of the primary channels required for the primary backup path.

5. More than one CGMS may use the same back-up path.

6. Approximately 5% of the CTAG calls transiting ARTCC areas will not be switched by the local CGMS. They will be switched by the CGMS of the area into which the aircraft is entering.

The average number of end-users connected to a CGMS is approximately 400. It is assumed that approximately 5% of these end-users will require simultaneous connectivity to aircraft connected to "foreign" cell sites, i. e., those not directly connected to the CGMS.
Tables 13-1, 13-2, and 13-3 were used to determine the transmission requirements.

Table 13-1 Number of End-Users Requiring Back-Up

CGMS Utilization	Number of Users	Number of T-1 Connections Required (each T-1 = 24 • 64-kb/s channels)
Maximum	500	20.8 + "foreign"* (1.2) = 22
Average	400	16.7 + "foreign"* (1.3) = 18
Minimum	300	12.5 + "foreign"* (1.5) = 14

*"foreign" = cell sites not directly connected to primary CGMS

Table 13-2 CGMS Utilization by Location

Maximum	Average	Minimum
New York, NY	Boston, MA	Miami, FL
Washington, DC	Cleveland, OH	Jacksonville, FL
Atlanta, GA	Memphis, TN	Indianapolis, IN
Chicago, IL	Kansas City, MO	Houston, TX
Fort Worth, TX	Salt Lake City, UT	Minneapolis, MN
Los Angeles, CA	Seattle, WA	Albuquerque, NM
Oakland, CA		Denver, CO

Table 13-3 CGMS Alternate Locations

CGMS	Primary Back-Up	Secondary Back-Up
New York, NY	Washington, DC	Boston, MA
Washington, DC	Indianapolis, IN	Atlanta, GA
Boston, MA	Cleveland, OH	New York, NY
Cleveland, OH	New York, NY	Boston, MA
Indianapolis, IN	Washington, DC	Chicago, IL
Chicago, IL	Minneapolis, MN	Cleveland, OH
Minneapolis, MN	Kansas City, MO	Chicago, IL
Kansas City, MO	Denver, CO	Minneapolis, MN
Memphis, TN	Kansas City, MO	Atlanta, GA
Atlanta, GA	Memphis, TN	Jacksonville, FL
Jacksonville, FL	Atlanta, GA	Miami, FL
Miami, FL	Jacksonville, FL	Houston, TX
Houston, TX	Fort Worth, TX	Miami, FL
Fort Worth, TX	Albuquerque, NM	Houston, TX
Albuquerque, NM	Los Angeles, CA	Fort Worth, TX
Denver, CO	Salt Lake City, UT	Kansas City, MO
Salt Lake City, UT	Seattle, WA	Los Angeles, CA
Los Angeles, CA	Salt Lake City, UT	Albuquerque, NM
Oakland, CA	Los Angeles, CA	Seattle, WA
Seattle, WA	Oakland, CA	Salt Lake City, UT

13.1.2 Switch Type, Hierarchy, and Location

The CGMS is a fully digital, private branch automatic exchange (PABX) type of circuit switch, capable of switching standard (CCITT G.711) 64-kb/s pulse code modulation (PCM) voice channels in a transmission environment similar to that of the public switched telephone network. The CGMS must be able to handle between 2000 and 5000 input lines. Representative PABXs in this line range are the AT&T System 85 and the Northern Telecom SL-1.

The CTAG switching hierarchy is proposed to have two levels. The local level consists of the cell site switches; it distributes communications to each of the end terminals. These cell site switches are connected to a primary level of backbone switches, described above as the CGMS equipment.

A three-level switching hierarchy was considered, but not adopted, as addition of a third level would not necessarily improve network availability or robustness, and would add considerable complexity to the problem of switch signaling and control.

Each CGMS should be located at a major communications node of activity of the FAA air traffic control system. Immediately the locations of the present-day Air Route Traffic Control Centers (ARTCCs), which will, under the National Airspace System (NAS), evolve to become Area Control Facilities (ACFs) qualify, since not only are they FAA owned and maintained, but already have major entry points into air traffic control communications networks. Collocation of CTAG ground system assets with other FAA ATC equipment at the ARTCCs will greatly simplify site preparation, operation, administration, maintenance, provisioning, and interface requirements. In the conterminous 48 United States there are 20 ARTCCs, and one each in Alaska and Hawaii. In addition, there are 7 regional air traffic control facilities in Canada. However, if one considers only the United States for the scope of CTAG for sizing purposes, this limits the number of CGMSs to 20 + 1 + 1 = 22 circuit switches, of class 5 size or less (subsequent choice was a PABX-sized switch of between 2000 and 5000 lines), geographically distributed approximately evenly across the United States. This is shown by the map in figure 13-1.

Since each switch must be at least doubly-connected with other switch installations for backup purposes, it may be desirable to introduce two additional CGMS sites at the locations of major nodes that nevertheless have no ARTCC (see figure 13-1). This then raises the possible number of large circuit switches in the CTAG ground network to 24. However, for present CTAG system baselining purposes, we treat the number of CGMSs to be 20, one per ARTCC site. Future analysis will determine the necessity of additional switch locations.

13.1.3 Inter-Switch Signaling

The standard inter-switch signaling system optimized for modern digital switches is the set of specifications known as common channel Signaling System #7. This set of procedures has been developed by the International Telegraph and Telephone Consultative Committee (in French, Comité Consultatif Internationale Télégraphique et Téléphonique, or CCITT) for both international and domestic use to control digital stored-program control (SPC) telephone

switches. It is designed to replace Signaling System #6, which was developed for the previous generation of analog SPC switches. Therefore, this is the signaling system which will be proposed for use by the CTAG ground switch network. This system is, essentially, a data link between switches operating at 64 kb/s, which transfers packetized signaling information on a signaling channel separate from the channels that carry digital voice or data traffic. The traffic on the trunks of the switch is also ordinarily transmitted at 64 kb/s, using pulse code modulation (PCM).

13.1.3.1 Signaling System #7

Signaling System #7 is an entire set of signaling protocols that have been specialized to perform call setup, signaling , supervision, connection, and disconnection, and internetwork operation, administration, maintenance, and network management functions for a digital circuit-switched network based upon 64-kb/s traffic and signaling paths (or trunks, circuits) [Reference 2]. It is divided into several parts:

- Message Transfer Part (Data Link Protocol)

- Signaling Channel Connection Part (Network Layer Protocol)

- User Parts (Higher-layer functions)
  - Corresponds to each "service"
  - e. g., Telephone User Part (TUP), Data User Part (DUP), ISDN User Part (ISUP)

- Application Parts (End-Applications)
  - Corresponds to each specialized function contained as an "end application" in the network
  - e. g., Mobile Application Part (MAP), Operation & Maintenance Application Part (OMAP)

Signaling System #7 allows call setup and supervision to be performed without consumption of a traffic-bearing trunk, and also without the "in-band" or in-channel signaling which is performed in the previous generation of signaling systems. Signaling System #7 messages query a constantly updated database maintained at every switch site on the available unblocked routes for a potential call. If all available call routing paths are in use, the system immediately relays a call blocked message to the originating switch. Similarly, if there is a path open, it is allocated to the requesting call, the database of connections is updated, and the call attempt signal is put at once onto the traffic channel. Measured interval between cessation of subscriber dialing of call digits and sensing of ringing on the line in European and North American test systems is on the order of tens of milliseconds, a far faster performance than the one to three seconds required for switch-to-switch call setup and cut-through under the present signaling system (#6).

By and large, Signaling System #7 is used based upon the assumption that the digitization of the (signaling occurring in the) local loop is being slowly phased in. That is, the analog public switched telephone network (PSTN) between the end-office switch and the subscriber is being converted into an integrated services digital network (ISDN). Two major characteristics of an ISDN (which to a normal voice subscriber would look like an end-to-end

digital network, but carrying voice) is that the local loop signaling is digital, and that there is enough "smarts" in the network to handle the greater speeds of connection allowed by digital inter-switch signaling. The "smarts" is the processing power required to not only process the multitude of special packetized messages being transmitted from switch to switch, but also the processing associated with maintenance and updating the database of call connections.

Further information is given in the CCITT Blue Book, in the CCITT Recommendations of the Q.700-Series and the Q.1000-Series.

At the present time, each interexchange carrier (IXC) and most of the local exchange carriers (LECs) are experimenting with American "standard" implementations of Signaling System #7. However, end-to-end calls under full Signaling System #7 control must await what appears to be multiple bilateral agreements between carriers at the interface between the LEC and the IXC.

As with all developing standards and protocols associated with integrated services digital networks (ISDNs), Signaling System #7 is compliant with the Open Systems Interconnection (OSI) reference model for CCITT applications, Recommendation X.200 [Reference 3].

13.1.3.2 Application of Signaling System #7 to CTAG

It is assumed that the traffic would be switched at a 64-kb/s rate (as do all modern digital switches). This requires that at some point, the digitized voice traffic streams have been converted from lower-rate digital voice to standard 8-bit PCM. This is not a problem as there are several places that this could occur without impact on performance.

Interworking between different systems is not a consideration in CTAG, since the CTAG ground network is a single, "private," network. Therefore, inter-system handoff procedures are ignored here. However, we are concentrating on the protocols used for potential switch-to-switch (i. e., CGMS-to-CGMS) handoff, and base station-to-base station handoff.

The switches upon which Signaling System #7 would be supported range from the large regional switches to the present generation of local central office switches, such as the AT&T #5ESS and the corresponding switches of Northern Telecom. In general, these central office digital switches would not have the specialized equipment required to process calls and handoffs in a cellular or trunked radio environment, and the processor units manufactured today would not handle Signaling System #7. However, all the major switch manufacturers, such as AT&T, Northern Telecom, ITT, Siemens, Thomson-CSF, L. M. Ericsson, Philips, Hitachi, Fujitsu, and NEC, have committed to implement Signaling System #7 in their central office switches. Switch control of the CGMS (CGMS-to-CGMS handoff) can easily be accomplished by Signaling System #7, and it appears that much of the Mobile Application Part (MAP) is applicable to the CTAG switching environment. However, it will require a considerable effort to determine the special processing required for base station-to-base station handoffs and control of airborne radios.

13.1.3.3 Signaling System #7 Software Modifications for CTAG

Signaling System #7 would operate on the data link channels between main switches, i. e., over the CGMS-CGMS inter-switch links.

The issue of modifications to standard digital circuit switch stored program control software is an important one, especially since performance of the increasingly used interswitch common channel signaling scheme, Signaling System #7, has been called into question. It is true that massive failures of voice communications systems that (1) made use of Signaling System #7 and (2) were used by the air traffic control system have been in the news recently. The problems of interexchange telephone carrier lack of alternate routing and switchover to backup systems in emergencies have also been documented. The problems with Signaling System #7 have been have been due, almost entirely, to inadequate testing of software before deployment, not to intrinsic defects inherent in Signaling System #7. Actual modifications to code were made to several software modules, and these modifications were released to an operational system without full-scale system tests.

Unlike the above interexchange common carrier services used by FAA communications, CTAG will be a private system, with no inter-system switch control data passing over its signaling network. This in itself will prevent any inter-system propagation of signaling error that occurs when two public systems interact. In addition, CTAG would make a different use of Signaling System #7 in another respect. For CTAG, Signaling System #7 will have to be adaptive,because of the unique and critical nature of CTAG, and because of the stringent FAA-mandated criteria of service availability and system restoral time. Thus the baseline signaling system found in the PSTN (and future ISDNs) would require some degree of software modification. The rewritten software would, certainly, have to undergo stringent testing under testbed and limited operational environments before it would be released into an operating CTAG.

13.1.4 Link Characteristics

There are two types of ground transmission links in the CTAG grouna system: the links between the cell site switches and a CGMS; and the CGMS-CGMS inter-switch links.

The access lines between the cell site switches will be dedicated digital lines operating at a 64-kb/s rate. Interface equipment between the cell site digital equipment and the transmission facilities would consist of the usual data service unit and channel service unit (DSU/CSU) combination, which provides conversion of unipolar binary data to bipolar coding, framing and synchronization, and which provides for channel monitoring and fault alarms.

The inter-CGMS trunks will consist of from seven to twenty-two T-1 carriers, assuming that each voice channel is transported in the inter-switch network as a 64-kb/s PCM bitstream. According to the AT&T definition (AT&T Standard Nº 365-200-100, © 1987, AT&T), a T-1 digital line is a facility for digital transmission between digital terminal locations. The rate of bipolar digital transmission using time-division multiplex PCM on the T-1 digital line is 1.544 Mb/s, which in the North American digital signal hierarchy is called the DS-1 rate. Reference 4 contains a brief summary of T-1 link operation.

13.2 SWITCH SIZING AND CONNECTIVITY

All CTAG ground-to-air-to-ground circuits are considered "critical," and the size of the CTAG switches and the number of interconnecting trunks are driven by the requirements for 0.99999 service availability, restoral of service in six seconds, and continuous pilot access to NAS facilities. Quantities in this section are to be considered "bounding" quantities, i. e., numbers that would characterize an essentially non-blocking system.

As stated in the previous section, the CGMS backbone consists of a set of 20 nodes connected by a mesh of high-speed trunks. There are approximately 1100 cell sites in the contiguous 48 United States, and 20 ARTCCs. Thus a CGMS serves an average of 55 cell sites. The cell sites receive their connectivity through trunks radiating from the CGMS nodes.

While this network must span the continent, and although there are at any one time several thousand commercial airplanes in the air at once over the land area of the United States, the air traffic air/ground system has several orders of magnitude less traffic than that of the PSTN. Accordingly, although there are to be 20 major circuit switches and 1100 cell site switches, in the proposed CTAG ground network, there will be much less traffic than in the nationwide telephone network, and very little that is analogous to the "local loop" except the cell sites/base stations.

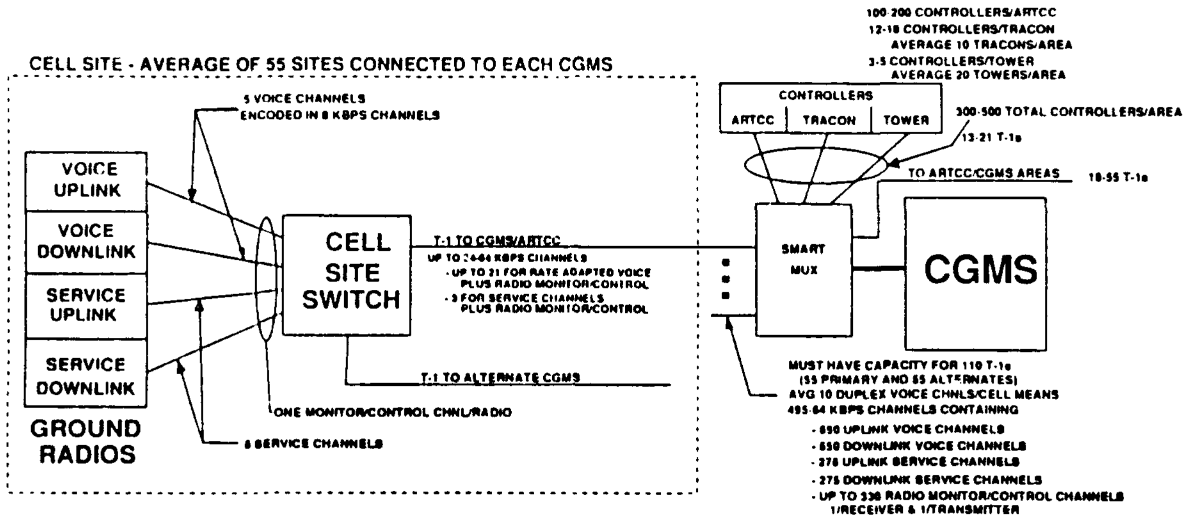
The traffic study [Reference 5] cites a model for United States ground/air voice conversations between controllers and pilots/aircraft. This will be factored in when traffic loading is determined.

13.2.1 Cell Sites

This model assumes that there is one cell site per radio installation location, yielding 1100 total cell sites. This assumption is made to simplify site acquisition, preparation, and maintenance, since it is hoped that the majority of proposed cell sites are already FAA VHF radio tower assets. The cell site (small) switch controls the ground radios via signaling information transmitted from the CGMS. The cell site switch itself (see figure 13-2) is a relatively simple equipment configuration, consisting mainly of rate adaption equipment, multiplexers/demultiplexers, and a switch matrix and its control processor. The cell site switch characteristics are outlined in more detail in section 14.3.

For robustness of the cell site to CGMS connectivity, it is assumed that each cell site is connected to two CGMS areas, so that in case the primary CGMS fails, a cell site may trunk calls to the alternate CGMS. Additionally, each cell site must have a complete set of redundant software and hardware modules, radios, uninterruptible power supplies (UPSs) and power conditioners, and antenna hardware (such as feeds, impedance match networks, and diplexers).

For each cell site, a minimum set of four frequencies is provided: the voice uplink and downlink frequency pair (f_u and f_d) carries 5 voice channels, which use a 4.8 kb/s code-



NOTES

CELL SITES CONNECTED TO TWO CGMS AREAS
CELL SITES HAVE REDUNDANT SW MODULES, RADIOS, UPS, ETC.
EACH CGMS AREA IS CONNECTED TO AT LEAST TWO OTHER AREAS
ASSUMES 1 CELL SITE/RADIO LOCATION & 1100 TOTAL SITES
CELL SITE SWITCH PROVIDES RATE ADAPTION, MUX/DEMUX & ALT SWITCHING
CELL SITE SWITCH CONTROLS GROUND RADIOS VIA SIGNALING FROM CGMS

Figure 13-2. CGMS to Cell Site Connectivity

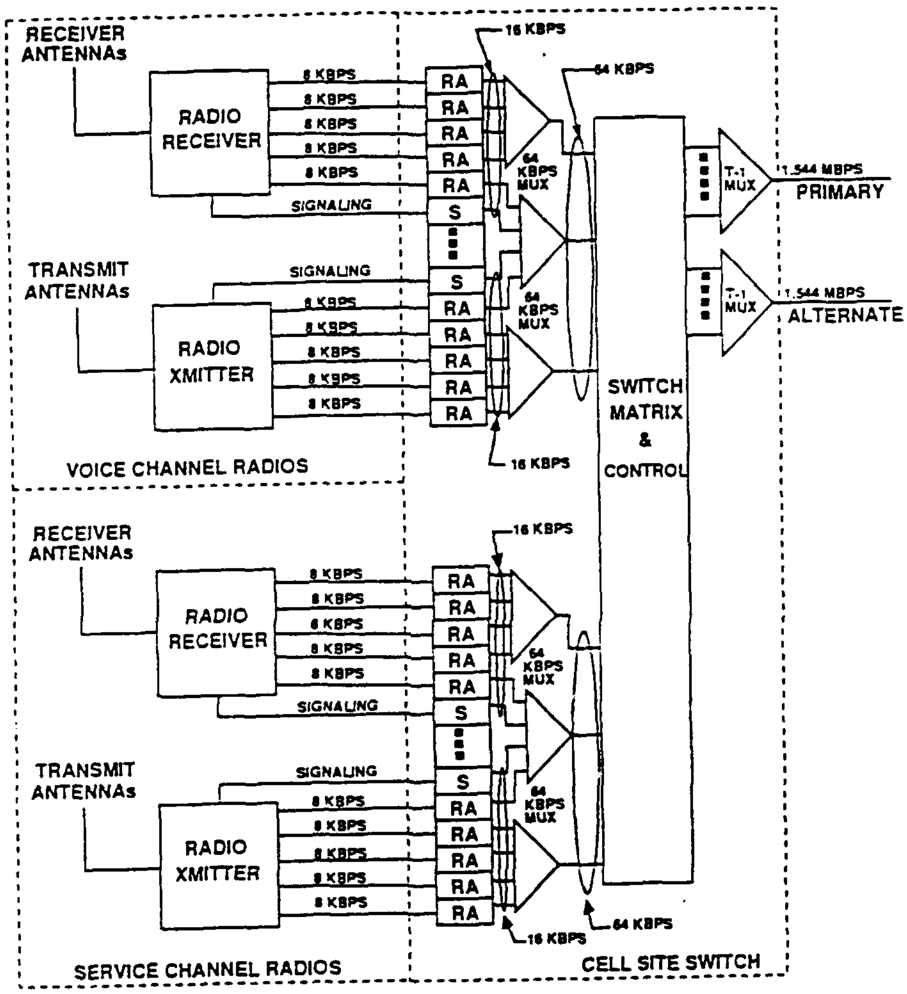
excited linear predictive (CELP) modulation scheme; and the service uplink and downlink frequency pair (f_{su} and f_{sd}), which provide 5 service channels. Although the voice source rate is 4.8 kb/s, with coding the channel rate is 8 kb/s. This does not include any framing for wireline transmission and multiplexing.

The voice channels will be rate-adapted according to CCITT Recommendations I.412, I.460, and I.463/V.110 to the next submultiple of 64 kb/s, that is, 16 kb/s, to introduce framing that preserves bit sequence integrity when multiplexed. Thus, although the raw traffic rate from the radios is 5 x 8 kb/s = 40 kb/s for the uplink, and 40 kb/s for the downlink, the ground system rate is greater. The raw service channel transmission rate has also been designed as 40 kb/s for both uplink and downlink, so the following argument will apply to both the voice/data and service channel radios.

From the radio receiver, after framing, the aggregate information rate is 96 kb/s = 5 x 16 kb/s for the voice channels and an assumed 16-kb/s digital channel (see note) for signaling between the switches and the radio equipment for control. This six 16-kb/s channel structure is also reflected from the radio receiver (NOTE: There should be one monitoring and control channel per ground radio. The signaling rate of this channel can be relatively low, i. e., 16 kb/s, and its characteristics may be similar to that of the packet-mode "D" channel for user-network interface signaling in an integrated service digital network.). Thus, the minimum traffic may be transmitted as six 64-kb/s channels from the cell site (small) switch: three for the rate adapted voice bitstreams, and three for the service channels and a cell site monitor and control channel. 64-kb/s DS-0 multiplexers/demultiplexers are proposed for simplicity; such multiplexers are standard for digital voice traffic. As is seen in figure 3, four of the rate-adapted voice channels share one multiplexer on the receiver side, and four share another on the transmitter side. The fifth receiver and transmitter channels, as well as the receive and transmit signaling channels, are multiplexed by a third multiplexer. This structure is also reflected in the service channel radio block diagram. However, the service channels are shared by many voice channels. This implies that the capacity of the cell site for voice channels may be maximized by adding six more pairs of voice channel radios (seven pairs in all), bringing the aggregate voice channel load per cell site switch up to twenty-one 64-kb/s channels (figure13- 4). Since three 64-kb/s channels are used by the multiplexed service channels, the total of 24 channels fits exactly into a single T-1 carrier at 1.544 Mb/s. For network robustness, the cell site switch would have a second T-1 carrier as an outgoing trunk, carrying the twenty-four 64-kb/s channels to an alternate CGMS, in case the primary CGMS fails. Note that each set of twenty-four 64-kb/s wireline channels represents an aggregate of 35 voice conversations and their associated service uplinks and downlinks. In addition, only one of the T-1 carriers would be in use at any one time, although both would be in a "hot standby" mode in the case of network impairment.

13.2.2 CGMS

There are 55 cell sites per CGMS, and each cell site transmits two T-1 carriers, each at 1.544 Mb/s. One T-1 provides the connection to the primary CGMS. The second T-1 carrier is only in use in the event of a primary CGMS failure. Thus, each CGMS should have the capacity to handle 110 T-1 carriers, 55 of them for the primary trunks and 55 for the alternates. Assuming that there is an average of ten full-duplex voice channels per cell (site),



NOTES:
SUFFICIENT CAPACITY IS PROVIDED IN SWITCH AND PATH FOR AN ADDITIONAL 6 RECEIVER/TRANSMITTERS (30 UP/DOWN LINK VOICE CHANNEL PAIRS
PRIMARY PATH IS CONNECTED TO NEAREST CGMS
ALTERNATE PATH IS CONNECTED TO ANY OTHER CGMS VIA LANDLINES
DIGITAL CONNECTIVITY PATHS ARE PROVIDED END-TO-END
RA = Rate Adapter, 8 TO 16 KBPS
S = Rate Adapter for Signaling, ? to 16 KBPS

Figure 13-3 CTAG Cell Site

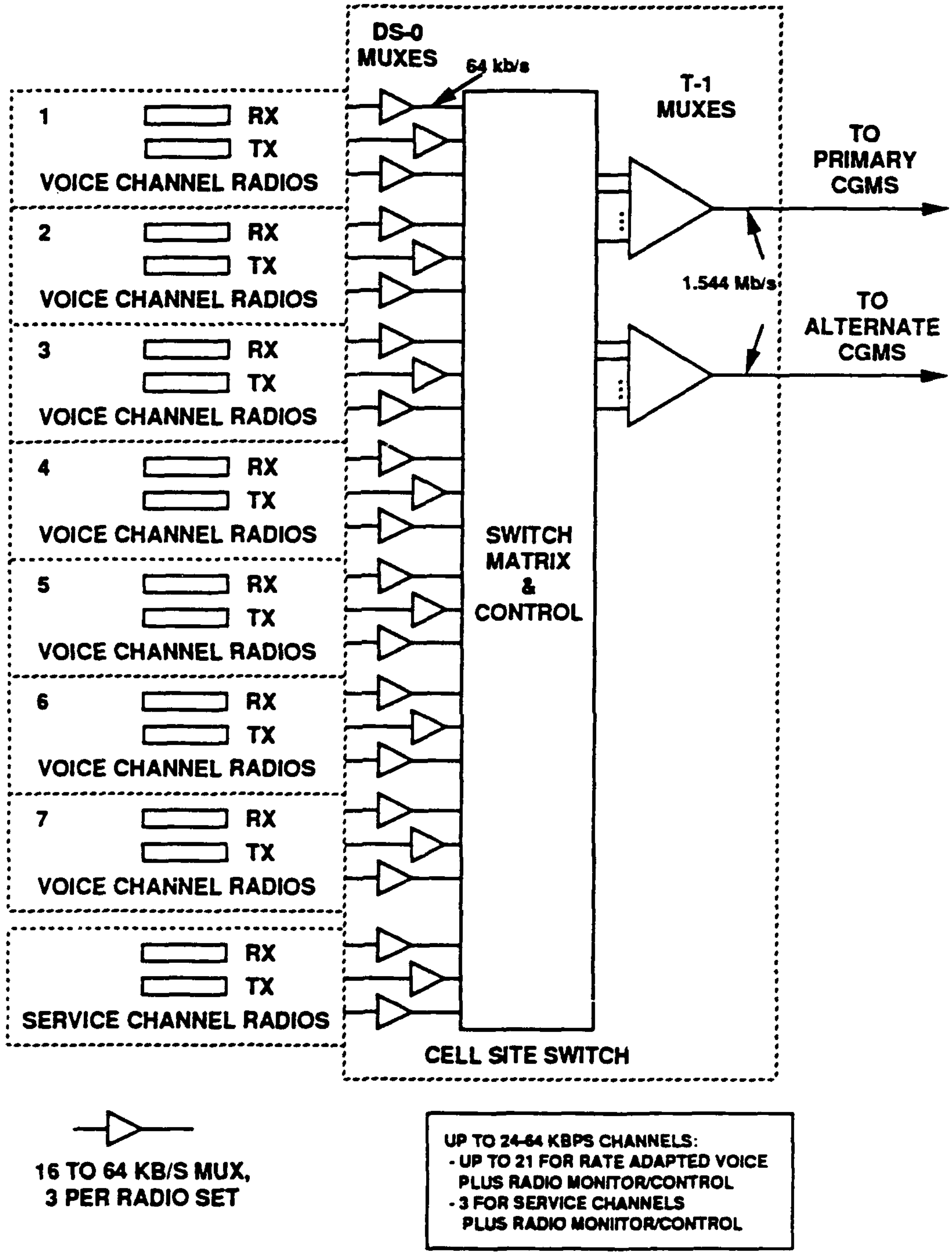


Figure 13-4. CTAG Cell Site Block Diagram

the cell site to CGMS connectivity represents 495 channels running at a 64-kb/s transmission rate, which contain:

- 550 uplink voice channels
- 550 downlink voice channels
- 275 uplink service channels
- 275 downlink service channels
- up to 330 cell site radio monitor/control channels (switch to switch control), one per receiver and one per transmitter,

for a total of 1980 channels to and from cell sites serviced by a CGMS. Figure 13-5 summarizes the channel breakout and connectivity at a CGMS site.

If one assumes that all ground controllers, whether at an ARTCC, a TRACON, or a control tower, require access to the air-ground radio system, one may allocate a rough count as to the number of controllers as follows:

- Controllers at the Air Route Traffic Control Centers (ARTCCs)
  For the 48 contiguous states, there are 20 ARTCCs. The number of controllers per ARTCC may vary from 100 to 200, depending upon the traffic through an ARTCC. The average number of controllers per ARTCC is assumed to be 150.

- Controllers at the Terminal Radar Control Centers (TRACONs)
  There is an average of 10 TRACONs per ARTCC area, the actual number varying from 8 to 12. With from 12 to 18 controllers per TRACON, the average number of controllers per TRACON is 15, and thus the average number of TRACON-associated controllers per ARTCC is assumed to be 10 x 15 = 150.

- Controllers at the Towers
  There is an average of 20 towers per ARTCC area, the actual number varying from 16 to 24. With from 4 to 5 controllers per tower, the average number of controllers per tower is 5, and thus the average number of tower-associated controllers per ARTCC is assumed to be 5 x 20 = 100.

Thus, there is an average of 400 controllers to be connected to the aircraft for air-ground radio communications per ARTCC area, representing from 300 to 500 controller subscribers. Table 3.2 reflects this average, and also the probable variance in traffic at each of the twenty ARTCCs. For traffic estimation purposes, it is assumed that there are three sizes of ARTCCs, "maximum" corresponding to 500 controllers per ARTCC area, "average" to 400, and "minimum" to 300. 300-500 controllers represents between 13 and 21 T-1 carriers of capacity between controllers and CGMS (300×64 kb/s + 1544 kb/s ≈ 13; 500×64 kb/s $\div$ 1544 kb/s ≈ 21).

In this design, controllers are connected to the CGMS through an intelligent access multiplexer, or "smart mux." As part of its functionality, this device allocates voice channels for each of the controller-ends of the radio channels. The controller-to-CGMS traffic assumes the previously cited 300-500 total controllers per area, a traffic load using from thirteen to twenty-one T-1 carriers.

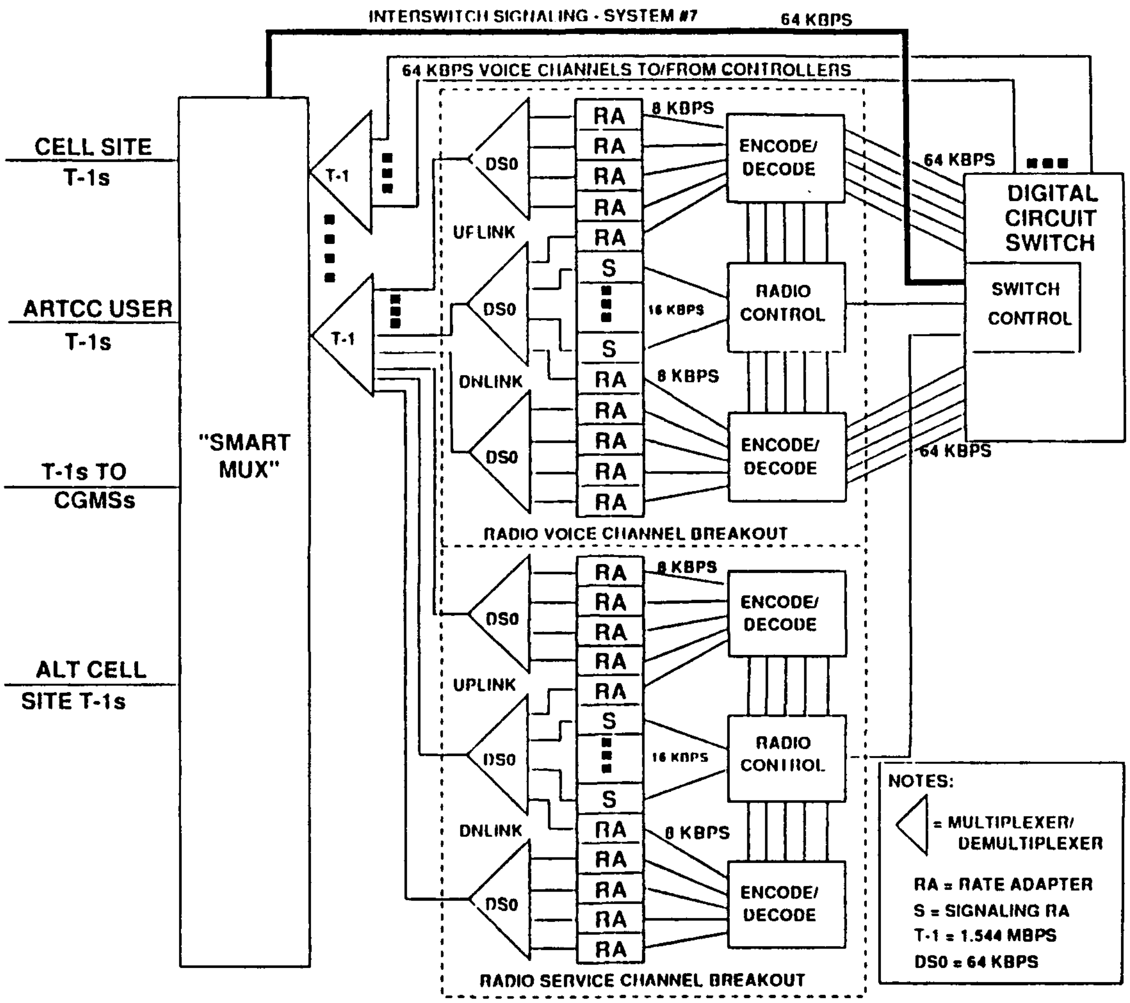


Figure 13-5. Channel Breakout and Connectivity - CGMS Site

In order to meet FAA availability and circuit restoral requirements, it is assumed that each CGMS area is connected to *at least* two other areas. This has been determined heuristically, although detailed traffic analysis could in the future provide a better estimate of switch to switch connectivity requirements.

13.2.3 Intelligent Access Multiplexer/Smart Mux

The smart mux is essentially a time-division switch. It has, essentially, four paths to the rest of the CTAG network:

- The cell site T-1 trunks
- The ARTCC users' T-1 carriers
- The T-1s that provide CGMS-to-CGMS connectivity
- The alternate cell site T-1s

The T-1 trunks from up to 55 cell sites are the primary conduits of the voice conversations to the CGMS. The ARTCC users are, essentially, the ground controllers, but not only those in the ARTCC facility, but also the controllers in the TRACONs and in each of the remote towers. The interswitch trunks carry voice channels for which adjacent cell sites have different primary CGMSs, as well as interswitch messages, and network management, operation, administration, and maintenance messages. Finally, the alternate cell site T-1s use the local CGMS as a backup. They are connected to the CGMS adjacent to the local smart mux in case that their primary CGMS fails.

It also has two paths to the digital circuit switch in the CGMS:

- The T-1 lines that carry the multiplexed voice channels from the cell sites
- The T-1 lines that carry the 64 kb/s voice channels to and from the controllers

There is yet another path between the digital circuit switch and the smart mux. It is a common channel that is a shared path containing the CGMS-to-CGMS signaling messages that uses the packetized Signaling System #7. The smart mux that provides ground controller access to the CTAG ground network is a critical assemblage, which must essentially exist in a "can't fail" mode. For controller-to-network connectivity, dual, or even triple, smart muxes should have interfaces in parallel to the CGMS, to allow for single unit failure.

13.3 NETWORK PERFORMANCE

The ground network portion of CTAG is characterized as a specialized switching and data processing operation. Provision of available radio channels for subscriber (pilot, ground controller) call attempts is only part of network operations. The interconnecting facilities and the telephone trunks that provide ground paths for voice communications must also support the requested call traffic. The ground path that a CTAG call assumes after a VHF radio link is established contributes as much to call quality as noise contributed by the radio equipment. Evaluation of a complete network call path from calling to called end, end-to-end, and under actual subscriber load, is a basic requirement to determine/ascertain overall network

performance [Reference 6]. In ordinary cellular telephone systems, system testing tends to be local to functional subsystems, such as switching, radio equipment, and interconnection (i. e., ground transmission), and these subsystems tend to be tested independently of one another. In CTAG, however, neither the controller nor the pilots view the ground system infrastructure at all, nor can any one of these end-users determine whether the switch, the cell site, the ground transmission, or the VHF coverage patterns are responsible for a hypothetical CTAG service problem. Experience in cellular telephone systems has shown that the mobile telephone switching office tends to receive much of the blame for system failures and troubles. Therefore, the entire CTAG voice path, from airborne radio to the FAA controller, must be modeled and analyzed to ensure that essential requirements can be achieved. Achievable design goals for the network with the architecture described are:

- Less than 100 milliseconds of delay from controller to ground radio input and vice versa
- Reestablishment of a failed voice channel ground path in less than three seconds, after detection of failure

For CTAG testing, CTAG system operators charged with maintaining high perceived network service levels should use test strategies that consider network performance from the end-user perspective. CTAG methods of system testing should provide some precise indication of trouble in the specific subsystems of the network that are susceptible to degradation under the varying network loads. Since the A/G communications function is considered a critical one in air traffic control operations, such testing is vital to network maintenance and restoral (NOTE: The U. S. Army's Mobile Subscriber Equipment (MSE) system uses such a test method. Certainly the FAA's A/G voice network will maintain the same level of requirements for reliability, availability, maintainability, and restoral as MSE.).

13.3.1 Switch Performance

The performance description of a medium-sized (up to 10,000 lines) modern digital PABX switch, such as an AT&T System 75 or System 85, or a Northern Telecom SL-1 or SL-100, may be taken as representative of the performance specifications required for a CTAG CGMS. Such a switch, as described in Reference 7, has as its foundation a voice and data circuit-switched digital subsystem under software control, which is comprised of a central processing unit, memory store, and a digital switching network that uses time division multiplexing and PCM techniques.

A cell site switch is actually an automated digital access cross-connect system, which provides redistribution of transmission facilities. It also uses time-division multiplexing and PCM techniques, and operates under Stored Program Control.

13.3.2 Link Performance

There are two types of transmission links that must be addressed by the CTAG ground system: transmission links between cell sites and a CGMS, and links between CGMS and CGMS. However, there is a unifying assumption: the line sections must be digital. To maintain the overall voice channel quality, the bit sequence integrity (BSI) of each of the

4.8 kb/s voice channels must be maintained throughout the switching and transmission systems. The purpose of rate adapting the 8 kb/s voice channel rate to 16 kb/s before multiplexing at the cell site switch is to place the coded bits into transmission framing for BSI maintenance at the cell site level. Similarly, the purpose of the framing and synchronization overhead which characterizes the T-1 carrier is to maintain BSI at the trunk level, as well as to incorporate switch-to-switch signaling.

Applicable CCITT (and now ANSI) standards for rate adaption from 16 kb/s to 64 kb/s, and transmission link performance at DS-0 (64-kb/s) and DS-1 (1.544 Mb/s) rates are found in the CCITT Blue Books, in the I.460 [Reference 8] and the G.730 [Reference 9] series, respectively.

13.3.3 Reliability and Availability

The FAA guidelines for reliability of the ground network are in terms of a system mean time between failure (MTBF). For typical switch reliability figures, Reference 10 illustrates typical reliability and MTBF figures for a Defense Switched Network (DSN) generic switching center (which is in size similar to a class 5 central office rather than a 2000- to 5000-line PABX). As defined by MIL-STD-781C, paragraph 3, the predicted MTBF for such a switch is:

- Catastrophic: 40,000 hours
- Major: 20,000 hours
- Minor: 720 hours

The upper and lower bounds for minor failures are 878 and 550 hours. Definitions for the terms follow:

- Catastrophic: Loss of call processing on ≥ 95% of equipped lines
- Major: Dial tone delay over 3 seconds on ≥ 20% of calls
  <u>or</u> post-dialing over 10 seconds for all interoffice calls
  <u>or</u> complete call processing loss to ≥ 5% of equipped lines or ≥ 50 equipped lines, whichever is less
- Minor: Dial delay over 3 seconds on 1.5% to 20% of calls
  <u>or</u> post-dialing delays on all interoffice calls of 1 to 10 seconds
  <u>or</u> complete call processing loss to < 5% of equipped lines or < 50 equipped lines, whichever is less
  or hardware or software faults that do not affect call processing to an extent greater than defined by the service requirements
  (Section 18 of Reference 10)

The FAA specification for system availability is 0.99999. Reference 10 states that for a switch, inherent availability achievable is at least 0.99996. This is the fraction of the total time that the switching system is able to perform its intended function. The system is not considered available under catastrophic and major degradations and failures. In order to meet the FAA specification for restoral, the ground network must allow restoral within six seconds of an outage.

The FAA requirements for reliability, availability, and restoral will be met by use of a multilevel approach. The following strategies are intended as examples of such an approach, but are not intended to restrict the approach only to these strategies. At the equipment level, redundant equipment and modules should be collocated at the sites of operational CTAG assemblies, both at the cell sites and the CGMS locations. At the electrical power level, all equipment that requires critical availability should be protected by automatic uninterruptible power supplies (UPSs). At the transmission plant level, the rich connectivity, both between cell sites and CGMSs and from CGMS to CGMS, should serve to increase reliability and availability of voice and control paths. Additionally, at the control level, alternate CGMSs (for cell sites) and primary and back-up CGMS paths (between CGMSs) should already be established, and be ready for cutover in the event a switch or connectivity failure is detected (this may be accomplished under stored program control, or manually).

SECTION 14

SWITCHING TECHNOLOGY AND EQUIPMENT

The primary candidates for the switching technology for CTAG were fast packet switching and circuit switching. Although a thorough tradeoff analysis was not accomplished, the following paragraphs provide the reasons for selecting circuit switching technology, and provide details regarding the switching equipment.

14.1 SWITCHING TECHNOLOGY

In response to the question, "What kind of switch should be used for CTAG," or, "Why not packetized voice,"the following subsection, with illustrative example, is pertinent.

Reference 11 cites that in the spring of 1988, Micom produced both a voice packetizer and a voice/data statistical multiplexer (stat mux). The packetizer, APV-1, allowed one "in essence" to transmit a voice channel as part of any synchronous 9.6 kb/s data link. The purpose of this device was to eliminate analog (leased) tie lines. The stat mux, Stat V, created voice packets that resemble data packets, allowing both to be transmitted over the same synchronous channel. Using a technique similar to TASI and DSI, the stat mux would transmit data in the pauses of voice transmission. The stat mux would handle up to 4 voice channels and a number of data configurations, and would address point-to-point applications. Transmission is over a single, leased, analog line using 9.6 or 19.2 kb/s DDS interfaces, or a 56 kb/s digital circuit, using standard CSUs and DSUs.

However, the price was quite high. The Stat V was priced near $5000, or about $1250 per voice channel. This is CPE cost, not including monthly line lease charges. The signal processing equipment for demultiplexing and recovering each voice channel takes processing time also. If a number of voice channels were in use simultaneously, i. e., if there were a condition in which there were no voice pauses, data rate would necessarily drop (as is typical of all stat muxes).

The uncertainty in response time in this technology is determined by the number of packets that have to contend for transmission. This system is designed for a fairly low duty cycle of voice traffic, less than 25%. The number of conversations will be high on a CTAG system, even though the voice duration time would be low. Reference 12, p. 5, discusses sources of delay in packet networks. There are four primary sources of delay in packet networks:

- Speed of light, ≈ 40 ms for the distance across the United States
- Packetizing: application-dependent, between 1-20 ms

- (Ordinary Packet) Switching: can be under 10 ms
- Queueing: $\approx n\,l / (s(1-\rho))$,
  where
  - n = number of nodes (typically, 2-100)
  - l = number of links (may exceed 100)
  - s = data rate (in b/s)
  - ρ= variable queueing parameter, $0 < \rho < 1$

A conventional packet network characteristically is designed for commercial data applications, that is, low-speed links with high error rates (voice-grade lines with modems, typically with bit error ratios of approximately 10^{-3} to 10^{-5}). Its switching and assurance of reliable transmission are implemented with general purpose computers that use robust, but complex, protocols. Such a network can support fairly high per-host costs.

A circuit switched network is characteristically designed for voice applications (and some packet-mode data). Its switching and reliable transmission are implemented with stored-program control special purpose computers using protocols in the signaling and supervision phases of a call. End-terminals are inexpensive. The expense resides in the switching, transmission, and control network.

Fast packet networks (the term in use today is "asynchronous transfer mode," or ATM) are being developed for high data-rate and high-bandwidth applications, and will come to the fore in the era of broadband ISDN. There are implementations, notably the switch by Stratacom, but are not yet widespread in the United States, pending stabilization of the protocol standards (in Europe, this is not the case; several large manufacturers, notably Thomson-CSF of France, has fast packet switches in operation presently) . These fast packet networks are designed for large networks that support voice, data, and video, in an all-digital transmission environment in which the network maintains a fairly good bit error ratio (less than 10^{-9}). This signal environment makes less robust, but "speedier," protocols effective. The performance requirements of such a network make these light-weight protocols necessary. The performance and cost objectives make VLSI-based switch designs (affordable and) essential. Much signal processing is done in the network and the switches.

Since the mandate of CTAG is to use only proven technologies, the major techniques for fast packet switching, such as frame or cell relay, asynchronous and synchronous transfer mode, were not considered for the CTAG switching architecture. Circuit switching technology was selected because of more mature protocols, wide usage in the United States, and expected overall lower cost. However, as fast packet networks progress, this entire area would be a worthy topic to reexplore.

14.2 CGMS EQUIPMENT

The CTAG Ground Master Switch (CGMS) essentially performs all the processing of calls, allocation of voice channels, and voice switching for the air-ground conversations in an ARTCC area. It will have the processing power upon which many of the functions of the cell

site switches rely. In addition, it will be handling four sources of input traffic: (1) the T-1 carriers from each of the approximately 55 cell sites that it serves (T-1 transmission rate of 1.544 Mb/s, but representing each up to 70 rate-adapted voice channels and ancillary service channels per cell site switch), (2) the lines from each of the ARTCC-based users, i. e., the 300-500 ground controllers in that ARTCC area, (3) the T-1 carriers for cell sites that use the CGMS as an alternate master switch, and finally, (4) the T-1 carriers that form the CGMS-to-CGMS backbone.

The sizing of the CGMS should be in the range of a PABX handling from 2000 to 5000 lines, but should also have the flexibility to be modular and expandable, as other functions and services are offered across CTAG.

The entire equipment train for a CGMS site would be a considerable requirements document. However, the major components would be as follows:

- Intelligent access multiplexers (at least 2) and necessary interface equipment

- T-1 multiplexers (one per T-1 carrier):
  - A maximum of 110 for primary and alternate trunks
  - From 13 to 21, to handle ground controller connectivity
  - From 7 to 22, for the CGMS-to-CGMS backbone (maximum at any one CGMS, per figure 1, 22 + 22 + 14 = 58)

- Encoding and decoding modules, to extract radio control and signaling information

- Main digital switch matrix and associated control processor equipment

- 16 kb/s to 8 kb/s rate adapters (according to CCITT Recommendations I.412, I.460, and I.463/V.110): approximately 1980 channels to and from cell sites per CGMS

- 64-kb/s multiplexers (three per radio set, either voice channel or service channel)

The CGMS site (figure 13-5) consists of the transmission plant interfaces for the T-1 carriers, the intelligent access multiplexers for interface with the ground controllers, the T-1 multiplexers, the 64-kb/s multiplexers that break out each individual voice channel, the 16-to-8-kb/s rate adaptors, the encode/decode modules, radio and switch control modules, and the digital circuit switch itself. Not shown, but also implied, are interfaces to the present and future NAS air traffic control ground communications, and to the PSTN.

The initial downlink and uplink voice channels at source code rates of 4.8 kb/s receive their own radio-based TDMA framing and coding, raising the channel rate to 8 kb/s. The processing performed on the basic voice channel in the ground network is merely to facilitate transmission, and to preserve the CELP BSI. To rate adapt the 8 kb/s downlink or uplink channels for multiplexing at the cell sites, local equipment imposes bit framing to yield a premultiplexed rate of 16 kb/s. DS-0 multiplexers combine four of these 16-kb/s bitstreams to yield composite 64-kb/s channels, and the T-1 multiplexers impose DS-1 framing and synchronization, as well as interswitch signaling, to yield 1.544 Mb/s bitstreams.

The T-1 carriers trunk in the framed and multiplexed voice channels from both the cell sites and the ground controllers to the CGMS. The smart mux is the source of connectivity between the ground controller T-1 trunks and the rest of the CTAG ground system, and it is in this device that transmission facilities are allocated. At the CGMS, the T-1 streams are demultiplexed into their composite 64-kb/s PCM channels, and before both the switch matrix itself and the control system, each separate voice downlink or uplink is stripped of its framing, leaving the original 8-kb/s voice channels, in two stages. DS-0 or 64-kb/s multiplexers demultiplex (for each radio set) the five voice downlink channel and associated signaling derived from the radio processor, the five voice uplink channels and associated signaling, the five downlink service channels and signaling, and the five uplink service channels and signaling, from the 64-kb/s datastreams, breaking out each individual voice or service channel as a 16-kb/s bitstream. Then, sets of rate adaption equipment are used to perform rate adaption of the 16 kb/s voice and service bitstreams to 8 kb/s. The control system removes the framing and control data from the voice channels, leaving the 4.8-kb/s CELP voice channel. It is not yet possible for the 4.8 kb/s voice stream to be "turned around" into an uplink channel. The information must still enter and leave the switch to be placed in the correct uplink channel.

The voice channels from the ground controllers may also enter the switch matrix by a different path. Each T-1 carrier from the ground controllers may contain "standard" 64-kb/s PCM digital voice channels from controller voice terminals. These voice bitstreams are demultiplexed directly into separate DS-0 bitstreams and directly input into the digital switch matrix, with appropriate signaling information input to the switch control modules.

At this point, the voice channel is still encoded at 4.8 kb/s CELP. For switching purposes, the encoding/decoding blocks rate-adapt the 4.8 kb/s digital signal (in a standard way, according to I.463) into a 64-kb/s bitstream. As this is rate adaption and not a change in encoding, the original CELP encoding is unaltered. It is this 64-kb/s bitstream that is switched.

An important function of the encoding/decoding blocks is to extract the radio control information embedded in the voice bitstream. This information is provided to the digital switch control modules as input. On the basis of the control information the individual 64-kb/s PCM channels are switched by the CGMS digital circuit switch matrix and control processors. Similar decoding and control information extraction is performed on the service channel bitstreams. This information is also provided as an input to the stored program control digital switch.

A voice channel, once switched by the CGMS, traverses the above signal path, in opposite order, to one of the multiple outgoing T-1 trunks, either to the primary or the alternate set of cell sites, or to the ground controllers, or to another CGMS.

There are a number of alternatives to provision of simulation of the "analog broadcast" function found in present-day VHF A/G radios. The one presented is an example of a simple design.The path to the user interface of the ground controller is where the voice channel suffers its only conversion, in the following manner. The switched signal destined for the controller may be rate adapted again, this time from a 64-kb/s replicated CELP bitstream to the original 4.8 kb/s one. It is at this point that the 4.8 kb/s CELP signal is converted to

64-kb/s PCM. This PCM voice channel is then multiplexed in the T-1 multiplexers and sent to the ground controller user interface.

Other alternatives and commentary follow. (1) One may "turn around" the downlinked channels to uplink channels in the cell site switch. This, however, would necessitate extraction of call control information, originally envisaged as a CGMS function, at the cell site, and would add to the complexity of the cell site switch. (2) One may also choose to send the 4.8-kb/s CELP voice channel directly to the ground controller user terminal. To do this, however, one would require modification of the ground controller receiver equipment, which is being upgraded to use 64-kb/s PCM voice. (3) The least practical solution is use of a 4.8-kb/s switch matrix within the CGMS. This would require design of an entirely new switch.

The CGMS should be sized to provide sufficient capacity to switch each individual channel in a nonblocking fashion.

CGMS-to-CGMS connectivity has been discussed in section 13. Continuous monitoring of main, primary back-up, and secondary back-up CGMS-to-CGMS trunks, so that upon detection of a backbone failure, stored program control in the digital switches may cut over the alternate routed trunks. The same argument pertains to CGMS-to-cell site connectivity. All transmission paths are via landlines (the choice of media is not a factor at this point). One important requirement is that end-to-end digital connectivity is provided. This means that every CGMS-to-CGMS trunk must be digital. Any analog path connectivity presents the possibility of line quality degradation due to excessive analog to digital and digital to analog conversion.

14.3 CELL SITE SWITCH EQUIPMENT

The CTAG cell site switch will not have the processing power of the CGMS, since at a maximum it must handle only twenty-four input lines of 64 kb/s each, and two output trunks, each a T-1 rate carrier at 1.544 Mb/s.

This does, nevertheless, represent a theoretical maximum of seven receiver-transmitter pairs for voice (plus associated service channels), or 70 voice channels, per cell site switch.

The entire equipment train for this cell site switch consists of the following:

- Receiver ground antennas (one per frequency, more if space diversity required)
- Transmitter ground antennas (as required)
- Radio receivers (one per frequency)
- Radio transmitters (one per frequency)
- 8 kb/s to 16 kb/s rate adapters (according to CCITT Recommendations I.412, I.460, and I.463/V.110)
- 64-kb/s multiplexers (three per radio set)
- A switch matrix and associated control processor equipment
- T-1 multiplexers (2)

The cell site switch (figure 13-3) consists of ten sets of rate adaption equipment, used to perform first-level rate adaption of the 8 kb/s voice and service bitstreams to 16 kb/s, with the addition of framing for BSI. The next stage of equipment multiplexes the five voice downlink channel and associated signaling derived from the radio processor, the five voice uplink channels and associated signaling, the five downlink service channels and signaling, and the five uplink service channels and signaling, into 64-kb/s datastreams. These composite 64-kb/s PCM channels are inputs to the cell site switch matrix and control processors, and are switched to one of the outgoing two T-1 trunks, either to the primary or the alternate CGMS.

Sufficient capacity should be provided in the cell site switch and its path for an additional six receivers and transmitters, representing 30 full-duplex, or up/down-link voice channel pairs.

The primary path is connected to the geographically nearest CGMS. The alternate transmission path is connected to any other CGMS. Both transmission paths are via landlines, in order to mitigate possible delay problems. Again, an important requirement is that end-to-end digital connectivity is provided. This means that every line section from the cell site to the CGMS must be digital. Any analog path connectivity presents the possibility of line quality degradation due to excessive analog to digital and digital to analog conversion.

SECTION 15

SIGNALING AND CONTROL

This section provides information on the proposed signaling and control for the CGMS ground system. Implicit in the information presented is that a portion of the signaling and control implementation requires a development effort for what is essentially custom software for a PABX-sized stored program control switch.

15.1 CALL PROCESSING

The CGMS contains the central processing unit which exercises call processing control over each of the air-ground voice conversations. The call processing performed by the CGMS essentially consists of three phases. The first phase occurs as an aircraft begins a flight, and hence enters the CTAG system. The second phase occurs as the flight is underway, and the physical ground link control transfers from cell to cell, or from controller to controller. The third phase occurs as a flight terminates successfully, and the aircraft voluntarily leaves the CTAG system.

At the entry phase of a flight, the pilot powers up the communications suite of equipment, and prepares to enter the CTAG system by requesting that a connection be made from that flight to a controller. The pilot selects the called party, i. e., the terminating location. It is assumed that the VHF CTAG radio possesses addressing capability, and that a request, for instance, for "Boston Tower," can be readily translated into the address of a specific controller in the correct sector that would monitor that flight through its initial phase.

In the en route phase of the flight, the CTAG ground system switches an individual flight from cell to cell by handoff procedures. Occasionally, adjacent cells that fall into different CGMS control areas would require that the ground signal path travel from cell site that the flight is leaving to that cell site's CGMS, then between CGMSs, then from the new CGMS to the cell site that is being entered. Additionally, handoffs from controller to controller are routinely performed as a flight crosses area boundaries or traverses different sectors of control.

At the terminal phase of the flight, the pilot again is reporting to a tower controller at a specific airport. As the flight itself terminates, the pilot powers off the communications equipment, logging off and leaving the CTAG system. The connection is properly terminated, and the databases are updated to the effect that the landed flight's address is no longer active.

15.2 HANDOFFS

Handoffs occur during cellular communications when coverage by one cell site is transferred to that of another. During the communications, the ground controller and the aircraft use a voice channel. When the aircraft leaves the nominal coverage volume (not just area; cells are

three-dimensional), reception quality parameters diminish. At this time the present cell site requests a handoff. The CTAG system switches the call to a new frequency channel in a new cell site without either call interruption or user alert. In the CTAG system, the call continues, and neither end-user perceives the occurrence of the cell-to-cell handoff.

An outline of proposed CTAG handoff procedures is contained in Reference 13, and the following description is extracted from it. Performance of cell-to-cell handoffs requires that the aircraft terminal scan all service channels and record a channel quality measure, which is reported every 2.4 ms in the embedded maintenance/emergency subchannel in the 4.8 kb/s CELP voice channel. It is proposed that the aircraft terminal passes a message consisting of flight number and cell quality parameters to the cell site radio terminal. Processors in the radio terminal at the cell site would provide the ground system with a voice downlink frequency, voice channel number, controller identification, measure of bit errors decoded in the received maintenance/emergency message. These messages are send to the CGMS.

Meanwhile, the CGMS maintains a database of connections, which includes, among other entries, the aircraft flight number, present associated call number, present cell quality measure, and a table of the cell site numbers of all calls connected to the present ground controller. The CGMS updates its databases with the incoming maintenance/emergency and quality measure data. If one assumes that the "current cell quality" is determined to fall below an acceptable level for a long enough time (hysteresis must be designed into the handoff process criteria; otherwise, handoffs would continue on a continuous basis if an aircraft were flying "on the boundary" of two CTAG cells), the handoff procedure occurs, as follows.

The switch database is used to select candidates for the new cell site to which the handoff would be made. The CGMS then sends a message to the aircraft containing the new cell site number on the uplink maintenance/emergency subchannel embedded in a CELP voice channel. The new cell site message is sent to the present cell site, its radio terminal, and the aircraft terminal, along with the control data message containing the cell site number, uplink frequency, and voice channel number. The processor in the aircraft terminal then initiates round trip ranging on the new cell, to provide a degree of range correction for the TDMA synchronization. For the aircraft terminal and controller point-to-point conversation, the cell site radio terminal provides a service channel number and the TDMA range correction. The data then transferred on the service channel from the new cell site to the CGMS is the flight and controller identification, cell site number, service channel number, and range correction. With this information, the stored program controller for the CGMS should be able to assign a new voice channel associated with one of the service channels. Data to be transferred are voice frequency (downlink/uplink) frequency pair numbers, voice channel number, local identification number, ground controller identification, flight number, and range correction (NOTE: for controller-to-controller handoff, this would be the identification of the new, or receiving, controller). The CGMS sends a message to the new cell site switch containing the new voice channel assignment control data. This information is passed to cell site radio equipment and to aircraft receiver. The control data from the ground system is used by the cell site radio equipment to set up a receiver on the downlink frequency. When the aircraft receiver is ready to transfer to the new cell site, an indicator is sent in the maintenance/emergency subchannel embedded in the voice channel. The ground radio terminal provides downlink frequency information, voice channel number, controller

identification, and control data as part of the "ready to transfer" message to the present cell site switch, and to the CGMS.

If necessary, the CGMS may provide a new voice circuit path to the new cell site, sending this information to the new cell site switch. If it is necessary to provide a new path to a new controller, the CGMS performs a controller-to-controller handoff and uses the identification of the new receiving controller in this sequence.

After preliminary information has been exchanged, the CGMS sends the message for the equipment to perform the handoff. This control data message (cell site number, uplink frequency, voice channel number) is sent to the old cell site switch, its ground radio terminal, and the aircraft radio terminal. When ready, the aircraft radio acknowledges as a final message on the old maintenance/emergency subchannel. The acknowledgment message flows to the old cell site radio terminal and its switch. The final message (downlink frequency, voice channel number, controller identification) is sent to the old cell site switch and to the CGMS. The CGMS updates system databases, and databases for the old and new cell site switches (if required), and switches, sending control data information finally to the new cell site switch (voice frequency downlink number and voice channel number, if required.

This sequence should establish a new end-to-end communications path between the airborne terminal and the new cell site switch, and the airborne terminal henceforward may access the new voice channel.

SECTION 16

CONCLUSIONS AND RECOMMENDATIONS

One of the major findings and conclusions from the CTAG ground system definition effort is that the CTAG ground network contains no "show stoppers" in terms of technology. However, an unmistakable conclusion is that the present ground network support for present-day ATC air-ground VHF radio operations will require an increased complement of ground network equipment to support a CTAG system, specifically, two sets of circuit switches and an increased set of end-to-end digital line sections and trunks.

This brief design analysis reveals that the proposed CTAG ground network system should have the following characteristics:

- The network should exhibit a two-level hierarchy of circuit switches.
- Each master site should have a CGMS that is a PABX-sized large digital switch.
- Each cell site should have a small switch, the radio equipment, and transmission lines.
- Common Channel Signaling System #7 should be used for call control and handoffs.
- New switch software development for CTAG-specific functions is required.

This study has resulted in a basic architecture for CTAG. However, a considerable amount of work remains in order to improve and refine the architecture and prove some of the heuristically defined solutions. If CTAG is to evolve into an implemented air traffic control system, the following must be accomplished:

- Perform a traffic analysis, particularly by computer simulation techniques.

  The yield from this activity would be a more realistic, and probably smaller, design for the transmission requirements. This activity is particularly amenable to computer simulation by use of network simulation packages, such as CACI's COMNET II.5.

- Work to define the precise handshaking between the switches, and the radio equipment and the switching equipment.

  This is an important phase, for its yield will be an estimate on the software that must be written to implement CTAG functions at the CGMSs.

- Determine the effect of voice encoding and translation at various points in the CTAG ground network.

- Prepare a CTAG ground system cost model and determine rough order initial and recurring costs.

- Determine CTAG network management and control techniques.

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VOLUME 3 GLOSSARY

ACF	Area Control Facility
ADPCM	adaptive differential pulse code modulation
A/G	air/ground
AMPS	Analog Mobile Phone System
ANSI	American National Standards Institute
ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
ATM	asynchronous transfer mode
ATN	Aeronautical Telecommunication Network
BSI	bit sequence integrity
b/s	bits per second
CAASD	Center for Advanced Aviation System Development
CCITT	International Telegraph and Telephone Consultative Committee (in French, Comité Consultatif Internationale Télégraphique et Téléphonique)
CDMA	code-division multiple access
CELP	code-excited linear predictive
CGMS	CTAG Ground Master Switch
CO	central office
CPE	customer premises equipment
CSU	Channel Service Unit
CTAG	Cellular-Trunked Air/Ground
DDS	Dataphone Digital Service; digital data service
demux	demultiplexer
DSI	digital speech interpolation
DSN	Defense Switched Network
DSU	Data Service Unit
DUP	Data User Part
FAA	Federal Aviation Administration
FDMA	frequency-division multiple access
ISDN	integrated services digital network
IXC	interexchange carrier
kb/s	kilobits per second
LEC	local exchange carrier
MAP	Mobile Application Part
Mb/s	megabits per second
MSE	Mobile Subscriber Equipment
MSR	MITRE Sponsored Research
MTBF	mean time between failures

VOLUME 3 GLOSSARY (Concluded)

MTSO	mobile telephone switching office
mux	multiplexer
NAS	National Airspace System
OMAP	Operation and Maintenance Application Part
OSI	Open Systems Interconnection
PABX	private automatic branch exchange
PCM	Pulse Code Modulation
PSTN	public switched telephone network
RCE	radio control equipment
RCL	Radio Communications Link
SPC	stored-program control
TASI	time associated speech interpolation
TDMA	time-division multiple access
TRACON	Terminal Radar Approach Control
TUP	Telephone User Part
UPS	Uninteruptible Power Supply
VHF	Very High Frequency
VLSI	very large scale integration
VSCS	Voice Switching and Control System

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